PATENT SPECIFICATION

706,716

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COMPLETE SPECIFICATION

Improvements in or relating to Refracting Media

We, WESTERN ELECTRIC COMPANY, INCORPORATED, of 195, Broadway, New York City, New York State, United States of America, a Corporation of the State of New York, United States of America, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

This invention relates to refracting devices for waves of various kinds, including electromagnetic and compressional, and more particularly, in the case of electromagnetic waves, to devices employing artificial media possessing an effective permeability and to the combination of such media with artificial dielectric media.

The fabrication and use of artificial dielectric media for electromagnetic waves has been described in our copending application Serial No. 664,672, in which conductive elements such as metallic spheres or discs are arranged in a three-dimensional array analogous to the molecular lattice of a crystalline dielectric. There is an electric polarization engendered in such an array of elements by an electromagnetic wave, that is equivalent in many respects to the polarization of a natural dielectric medium.

There are known to the art arrays of conductive elements which produce an effective permeability and may be characterized as constituting an artificial magnetic medium.

In accordance with the present invention artificial refractive media of various sorts are employed in making refracting devices for waves, elastic or electromagnetic. In the electromagnetic case, combinations of artificial dielectric media with artificial magnetic media may be used to produce compound artificial refractive media in which boundary reflections are materially reduced or substantially prevented.

In particular, the use of artificial permeability in combination with an artificial dielectric yields a refractive medium having the same impedance as free space but having a lower velocity of propagation for electromagnetic waves. Because the impedances of free space and this compound refractive medium are the same, reflections at the surface are substantially eliminated.

In the case of compressional waves, acoustic waves, elastic waves and the like, rigid elements take the place of the conductive elements in the arrays and the resulting media are useful in the delay and refraction of the particular kind of waves for which the device is designed.

A satisfactory theory of artificial refractive media may be based upon the lumped element circuit equivalents of certain structures associated with hollow pipe wave guides, from which a generalization leads to the consideration of arrays of elements in free space.

In the accompanying drawings:

Fig. 1 is a perspective view of a section of hollow pipe wave guide with barrier plates defining a slot perpendicular to the direction of the electric vector, together with a diagrammatic representation of the equivalent lumped circuit element corresponding to the slot, namely a capacitance;

Fig. 2 is a similar representation except that the slot is parallel to the electric vector and the equivalent dumped circuit element is a shunt inductance;

Fig. 3 is a perspective view of a section of hollow pipe wave guide having a channel-like extension in one wall and a series inductance as the equivalent lumped circuit element;

Fig. 4 is a perspective view of a section of hollow pipe wave guide having barrier plates arranged as in the lower part of

Fig. 1 together with a plurality of channel-like extensions like that in Fig. 3 and having an equivalent lumped circuit which is a low-pass filter;

Fig. 5 is a perspective view of a point beam antenna system comprising a plano-convex, circularly symmetrical, strip lens;

Figs. 6, 7 and 8 are, respectively, top sectional, side and front views of the lens included in the system of Fig. 5;

Fig. 9 is a perspective view of a channel-like element useful in practising the invention;

Fig. 10 is a perspective view of a section of hollow pipe wave guide containing a channel element like that of Fig. 9 embedded in a filling of dielectric material such as polystyrene foam;

Fig. 11 is a perspective view, partly in section, showing an array of channels in a frame;

Fig. 12 is a perspective view of a V-shaped element useful as an alternative to the channel-like element of Fig. 9;

Fig. 13 is a perspective view of a plano-convex lens constructed of V-shaped elements as shown in Fig. 12 embedded in discs of dielectric material such as polystyrene foam.

Fig. 14 is a perspective view of a lens similar to that of Fig. 13 but embodying strip elements as shown in Fig. 5 in addition to V-shaped elements as shown in Fig. 13;

Fig. 15 is a perspective view of a double concave refracting structure employing wave guides somewhat like that shown in Fig. 3, operated in a mode of transmission in which waves are accelerated rather than delayed and hence providing a structure which converges or focusses waves passing therethrough;

Fig. 16 is a view of the structure of Fig. 15 as sectioned upon a medial horizontal plane.

Referring to Fig. 1, there is shown a section of rectangular hollow pipe dielectric wave guide 20 with the longer dimension of the rectangular section shown horizontal. It is assumed that an electromagnetic wave to be propagated through the guide has its electric vector E oriented vertically as shown in the figure. Upper and lower barrier plates 22 and 23 respectively having conductive surfaces are shown defining a slot 24 which has its principal direction perpendicular both to the direction of the vector E and to the longitudinal axis of the guide. A slot oriented like the slot 24 is known to function in the guide like a shunt capacitance in a conventional transmission line, and the lumped element circuit equivalent of the structure is shown diagrammatically at the right in the figure by a shunt condenser 24 in a conventional line 25. Thus, a metallic constriction or iris in a hollow pipe dielectric wave guide, oriented as in Fig. 1, is the equivalent in many respects of a capacitive shunt in a two-wire transmission line.

Fig. 2 shows a metallic constriction or iris oriented at right angles to that in Fig. 1 with reference to the vector E. This arrangement is known to be equivalent to a shunt inductance in a two-wire line, as indicated diagrammatically at the right in the figure.

Fig. 3 shows a channel-like cavity structure 26 in the top wall of a rectangular wave guide 27, the channel having a depth in the direction of the electric vector somewhat less than a quarter wavelength at the desired operating frequency. This arrangement is known to produce the equivalent of a series inductance in a conventional transmission line.

Fig. 4 shows a rectangular wave guide 28 in which a plurality of cavity structures 29 similar to the structure 26 in Fig. 3 are provided together with a plurality of shunt capacitive structures 30 similar to the lower barrier plate 23 in Fig. 1. The structure of Fig. 4 is found to have as its lumped element circuit equivalent the circuit shown at the right in the figure, the series inductances 31 corresponding to the channel-like cavity structures 29 and the shunt capacitances 33 corresponding to the constrictions formed by the barrier plates 30. The structure of Fig. 4 is thus equivalent to a loaded transmission line having series inductances and shunt capacitances, i.e., a low-pass filter. Such a line can readily be designed to have its characteristic impedance equal to the characteristic impedance of the unloaded line and therefore can be connected into an unloaded line of the same construction without material impedance mismatch. Moreover, because of the presence of the series and shunt elements in the loaded section, the velocity of wave propagation in that section can be made materially smaller than that of the unloaded line.

More particularly, the shunt capacitance per unit length in the loaded section may be adjusted to compensate, in its effect upon the characteristic impedance, for the series inductance per unit length, while not compensating in its effect upon the velocity of propagation, analogously with lumped constant circuit theory. Thus, if L_0 is the series

inductance per unit length and C_o the shunt capacitance per unit length in the unloaded line, and L_1 and C_1, respectively, are the added series inductance and added shunt capacitance per unit length in the loaded section, the characteristic impedance Z_o of the unloaded line is

$$Z_o = \sqrt{\frac{L_o}{C_o}} \quad (1)$$

while the characteristic impedance Z_1 of the loaded section is

$$Z_1 = \sqrt{\frac{L_o + L_1}{C_o + C_1}} \quad (2)$$

By so proportioning L_1 and C_1 that

$$\frac{L_o}{C_o} = \frac{L_o + L_1}{C_o + C_1} \quad (3)$$

it is seen that

$$Z_1 = Z_o \quad (4)$$

when

$$\frac{L_1}{C_1} = \frac{L_o}{C_o} = Z_o^2 \quad (5)$$

The velocity of propagation v_o for the unloaded line on the other hand is

$$v_o = \frac{1}{\sqrt{L_o C_o}} \quad (6)$$

while the velocity v_1 for the loaded section is

$$v_1 = \frac{1}{\sqrt{(L_o + L_1)(C_o + C_1)}} \quad (7)$$

By comparison of equations (6) and (7) it is seen by inspection that positive values of L_1 and C_1 result in

$$v_1 < v_o, \quad (8)$$

that is, the velocity of propagation in the loaded section is less than that in the unloaded line.

It should be noted that at higher frequencies, other modes of transmission, not possible at lower frequencies, occur and the velocity of propagation for such modes may be greater than the velocity of propagation in the unloaded line.

Image formation in the top, bottom and side walls of the guide 28 in Fig. 4 transforms the loaded guide into the equivalent of a refractive medium of infinite extent consisting of arrays of channel-like cavity structures combined with arrays of conductive barrier strips. When the inductances and capacitances are proportioned as specified by equation (3), the resulting medium is refractive to electromagnetic waves and at the same time introduces no reflection loss at the boundary between the unloaded medium and the loaded medium. In other words, since the wave impedance of the loaded medium is equal to the wave impedance of the unloaded medium (or free space), there is no reflection loss to a wave passing across the boundary between the two media. The propagation velocity in the loaded medium however, is different from that in free space, so that lenses, prisms, etc., may be constructed from the loaded medium which are capable of focussing, diffusing or otherwise refracting electromagnetic waves of suitable wavelength, with substantially no attendant reflection loss.

The right-hand portion of Fig. 4 indicates diagrammatically the impedances of the loaded and unloaded line and the velocity of propagation in each.

Figs. 5, 6, 7 and 8, show a lens structure employing capacitive elements alone without combining inductive elements, as disclosed in our copending Application Serial No. 664,673. This structure is repeated here to illustrate one type of capacitive medium which may be modified in accordance with the present invention to produce a non-reflective refracting structure.

Referring to Figs. 5, 6, 7 and 8, reference numeral 70 denotes a unipolarized, circularly symmetrical, metallic delay lens comprising an array 71 of forty-nine conductive strip members 3 spaced apart a distance S_y along the Y dimension, and a distance S_z along the Z dimension, of a polystyrene foam medium 32. The forty-nine strips 3 are arranged in seven vertical panels 72 to 78 or, stated differently, in eight horizontal tiers 79 to 86. The foam medium 32 comprises eight vertically stacked slabs 87 to 94 which contain vertical slots for retaining the strips 3 and support, respectively, the eight tiers 79 to 86. Numerals 95, 96, 97 and 98 denote, respectively, the front plane, the back convex face, the optical axis and the point focus of the lens 70. As shown on the

drawing the lengths of the slots and the strips 3, and the depths of certain outer slots and the widths of the corresponding outer strips, are selected so as to conform to the convex contour of the back face 96 of the lens. Accordingly, while the number N of strips per unit area of the YZ section is constant throughout the array 71, the array includes fractional, as well as whole strips. Numeral 99 denotes a conical, point-type horn having its throat orifice positioned at the focal point 98 and connected by the dielectric guide 100 to a translation device 101.

In the operation of the system of Fig. 5, assuming the device 101 is a transmitter, energy is supplied by the transmitter 101 over guide 100 to the horn 99 and a wave having a vertical polarization 21 (electric vector) and a spherical wave front, is propagated towards the lens 70. The phases of the wavelets passing through the thick central or vertex portion of the lens are retarded a greater amount than the phases of the wavelets propagated through the outer thinner lens portion, and the wavelets arriving at the flat front face 95 are rendered cophasal. Stated differently, the outgoing spherical wave front is converted by the lens 70 to a plane wave front extending perpendicularly to the axis 97. In reception, the converse operation is obtained, and an incoming plane wave front having a propagation direction parallel to the axis 97 is transformed by the positive plano-convex lens 70 into a spherical wave front converging on the focus 98. Inasmuch as the lens 70 is circularly symmetrical, focussing action is obtained in all planes containing the axis 97.

Fig. 9 shows a channel-like conductive element which may be used in accordance with the invention to serve as the equivalent of a series inductance either in a hollow pipe wave guide or in free space. The element 34 may be made of sheet metal of any desired thickness or it may be made of metal foil, in which case it may be stiff enough to be self-supporting or it may be thin enough to require external support. In either case it should be thick enough substantially to prevent penetration of the wave from one surface of the foil to the other.

Fig. 10 shows the element 34 embedded in a filling 35 of dielectric material, e.g., polystyrene foam, inside a section of rectangular hollow pipe wave guide 36. Mounting flanges 37, 38 are shown for use in inserting the section 36 in a system of similar wave guides, either loaded or unloaded. Section 36 is thus inductively loaded and is filled, in effect, with an artificial inductive or magnetic medium comprising the channel element 34 and the polystyrene foam 35, the latter being shown partly cut away in the figure, Internal wave reflections at the walls of the wave guide 36 serve to produce in effect a magnetic medium of infinite extent filling all space. The structure of Fig. 10 has been found to be substantially the equivalent of that of Fig. 3.

Fig. 11 shows a two-dimensional array of elements 34 in free space surrounded by a frame 39 and each element 34 having a supporting rectangular core 40 of polystyrene foam which is in turn supported by the frame 39. The element 34 in this case may be of thin metal foil which requires external support such as is given by the foam material. The array of metallic channels acts for free space waves as the equivalent of a single series inductance just as a single channel element in an enclosed wave guide acts as a single series inductive element for waves confined within the wave guide. The shape of the channel element may be varied somewhat and may be **U**-shaped or **V**-shaped, for example.

Fig. 12 shows a **V**-shaped channel member 41 which performs substantially the same function as the member 34.

Fig. 13 shows a three-dimensional array of **V**-shaped members 41 supported by circular slabs 42 of polystyrene foam, the combination approximately filling the space of and conforming to the shape of a plano-convex lens. The lens is the substantial equivalent of one which might be made from a material having a permeability materially different from that of air or free space, an example of such being a material known by the trade name of "ferroxcube" and having a permeability greater than unity for electromagnetic waves. The velocity of propagation of the waves in a permeable medium depends upon the relation

$$\frac{v_0}{v_1} = \sqrt{\mu_r \epsilon_r} \qquad (9)$$

where v_0 is the velocity of waves in free space, v_1 is the velocity of waves in the permeable medium, μ_r the relative permeability of the medium and ϵ_r the relative dielectric constant of the medium. Equation (9) indicates that a medium with effective permeability greater than unity will slow down electromagnetic waves and it follows that a convex lens made of the permeable medium will cause a focussing of such waves. A lens built as shown in Fig. 13 was tested by means of

electromagnetic microwaves and found to perform as expected, that is, in a manner similar in its focussing effect to an artificial dielectric lens built as shown in Figs. 5 to 8 inclusive, and described in our copending Application Serial No. 664,672. The slabs 42 in the structure shown in Fig. 13 may be fastened together by any suitable means, e.g., with acetate cement, adhesive tape, etc.

Fig. 14 shows another plano-convex lens for electromagnetic waves, in this case comprising a combination medium having both artificial permeability and artificial dielectric constant. As in the structure shown in Fig. 13, the structure of Fig. 14 is built up from circular slabs of polystyrene foam in which are [illegible]ded **V**-shaped conductive elements [illegible] addition, each slab has attached to [illegible]f its flat surfaces a plurality of [illegible]l conductive strips 43 which impart the desi[illegible] dielectric constant to the composite art[illegible]al medium. The slabs 42 are fastened t[illegible]her in the approximate geometrical fo[illegible] of a lens and may be attached to a standard or back plate 44 of polystyrene foam which in turn may be supported by an insulating base plate 45. The **V**-shaped elements 41 impart the artificial magnetic effect the same as in the structure of Fig. 13, it being possible to secure equivalent effects whether the points of the **V**'s are oriented toward the planar face of the lens as in Fig. 13 or toward the convex face as in Fig. 14.

A lens constructed as in Fig. 14 has been found to focus electromagnetic waves in the expected manner and whereas either medium (dielectric or magnetic) by itself would produce strong reflections from the surfaces of the respective lens, the combination shown in Fig. 14 was found to operate with only negligible reflections from the surfaces.

Figs. 15 and 16 show a converging lens of the phase-acceleration type designed for use with certain modes of transmission. The lens is composed of an array of channel members 110 or other corrugated structure alternating with smooth plates 111. The members 110 and plates 111 are supported in any suitable manner, as by rings 112 and 113 and form an artificial transmission medium. The volume of space occupied by the medium is in the shape and form of a double-concave lens. On account of the fact that this structure accelerates the phase of a wave entering it, the properties of a concave lens in this medium are [illegible]ke those of a convex lens made of a [illegible]dium in which the phase of a wave is [illegible]ed.

[illegible]tructure of Figs. 15 and 16 is operative particularly with waves in which the modes of transmission are of higher order than the simplest fundamental or dominant waves.

Such of the structures shown which do not depend for their operation upon properties peculiar to electromagnetic waves as distinguished from compressional waves may be used with either type of wave. Only the structure of Fig. 2 is in fact not adaptable to strictly analogous use with either wave type. It is to be understood, of course, that a structure for use with compressional waves requires the necessary mechanical rigidity to reflect compressional waves from its surfaces and has no need of electrical conductivity, whereas the same or any other structure for use with electromagnetic waves requires the necessary surface conductivity and requires mechanical rigidity only to the extent that its parts be maintained in the desired positions relatively one to another. It is known of course, that some modes of transmission which are possible in the case of compressional waves are not possible in the case of electromagnetic waves, and *vice versa* for some other modes of transmission.

It is to be noted, moreover, that at the resonant frequencies of any structure, standing waves appear instead of travelling waves and absorption of energy and filtering action occurs. It is also possible at some frequencies to propagate waves in more than one mode either alone or simultaneously, which wave appearing depending in some instances upon the direction from which the resonant frequency is approached as the frequency is varied in the neighbourhood of the resonant frequency.

What we claim is:—

1. A device for changing the velocity of propagation of waves of radiant energy, comprising a plurality of recessed elements positioned within a bounded region of a medium of a given characteristic impedance, each said element being composed of a material having a characteristic impedance for said waves that is of a different order of magnitude from that of said medium, said elements being separated from each other by portions of said medium, which portions are interconnected for the transmission of said waves through said bounded region, said plurality of elements being distributed over an area transverse to the direction of propagation of said waves.

2. A device according to claim 1, in which the boundaries of said bounded region are of the shape of an optical re-

fractor.

3. A device according to claim 2, in which the boundaries of said bounded region are of the shape of an optical lens.

4. A device according to claim 1, 2 or 3, in which the recessed elements are interspersed with flat strip elements of said material, so that the resultant effective characteristic impedance of the device is given a desired value.

5. A device for changing the velocity of propagation of waves of radiant energy in a medium of a given characteristic impedance for said waves, comprising a plurality of channel-shaped elements arranged in a spaced parallel array, a plurality of strip elements in a spaced parallel array, a two-dimensional sub-array of said strip elements being interposed between two adjacent two-dimensional subarrays of channel-shaped elements, said channel-shaped elements and said strip elements each being composed of a material having a characteristic impedance for said waves that is of a different order of magnitude from that of said medium.

6. A device according to any of the preceding claims, in which said recessed elements each comprise a channel-shaped member.

7. A device according to any of the preceding claims, in which said elements are resonant at a frequency higher than the frequency of a wave to be refracted.

8. A device according to any of the preceding claims, for free space plane polarized electromagnetic waves, in which said material of which said elements are formed is conductive.

9. A device according to any of the preceding claims, for compressional waves, in which said elements are rigid.

10. A device according to claim 8, in which said elements are mounted in a solid dielectric medium.

11. A device according to claim 10, in which said solid dielectric medium comprises polystyrene foam.

12. A lens for electromagnetic waves, comprising a plurality of circular slabs the slabs having different diameters and the body built up of the slabs approximately filling the space of and conforming to the shape of a planoconvex lens.

13. A lens according to claim 12, including also a plurality of spaced conductive strips attached to one of the flat surfaces of each dielectric slab to impart to it a desired artificial dielectric constant.

14. A lens according to claim 12 or 13, in which said recessed elements are V-shaped.

15. A device or a lens according to any of the preceding claims, in which the recesses in said elements have depths a substantial fraction of the design wavelength and materially less than [illegible] wavelength.

16. A wave guide system compr[illegible] hollow pipe dielectric wave gu[illegible] plurality of cavity resonators form[illegible] recesses in a portion of the wall [illegible] dielectric wave guide and [illegible]stituting series inductive elements [illegible] operating frequency of said system and a plurality of partial barrier plates attached to another portion of the wall of said guide and constituting shunt capacitive elements at the said operating frequency.

17. A wave guide system according to claim 16, in which the effective values of series inductance and shunt capacitance are so proportioned as to make the characteristic impedance of the system substantially identical with the characteristic impedance of the said dielectric wave guide as unmodified by the presence of said series inductive and shunt capacitive members while making the velocity of propagation of waves materially different from that in the unmodified guide.

18. A wave guide system constructed and adapted to operate substantially as herein described with reference to and as shown in Fig. 4 of the accompanying drawings.

19. A lens constructed and adapted to operate substantially as herein described with reference to and as shown in Fig. 13 or 14 or Figs. 15 and 16 [illegible]

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Fig.1.

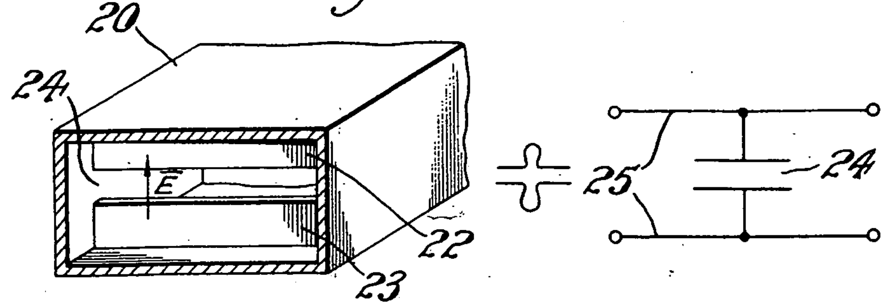


Fig.2.

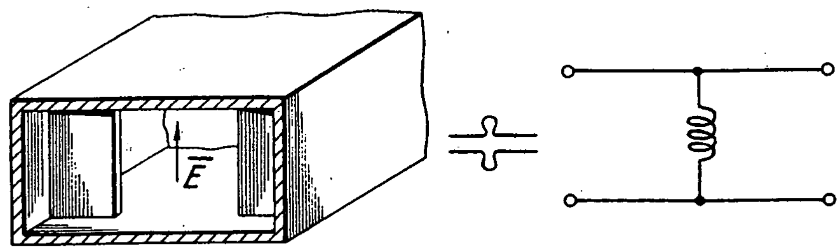


Fig.3.

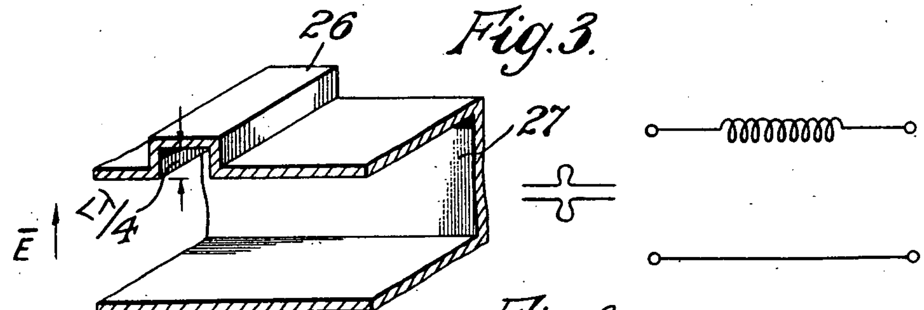
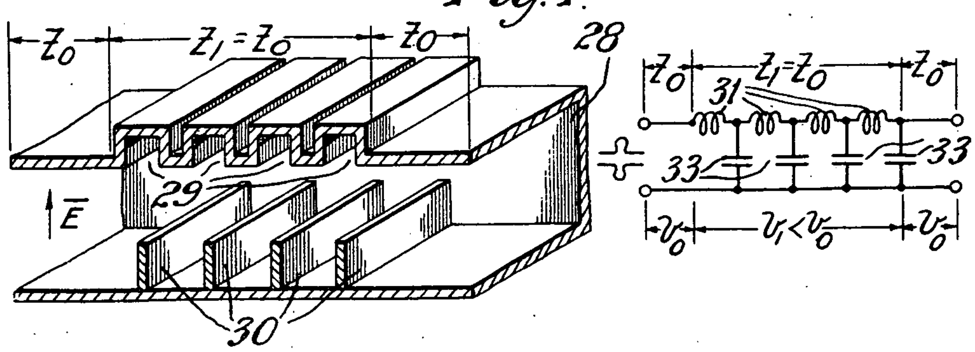


Fig.4.



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SHEETS 1 & 2

Fig.5

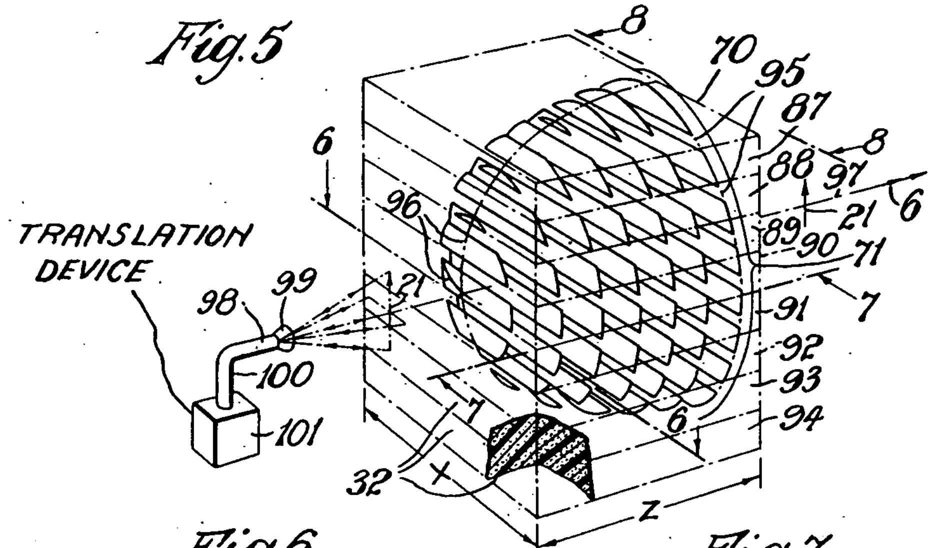

Fig.6.
TOP SECTIONAL VIEW OF LENS 70

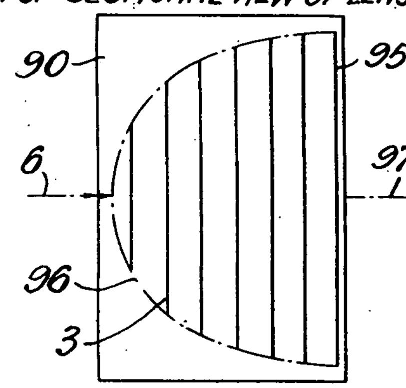

Fig.7.
SIDE VIEW OF LENS 70

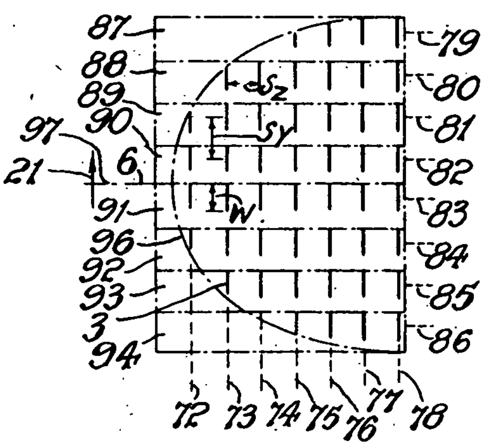

Fig.8.
FRONT VIEW OF LENS 70

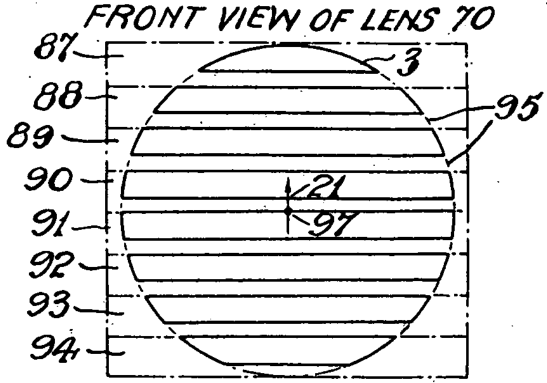

Fig. 9.

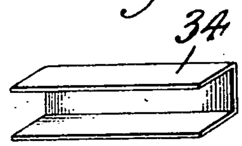

Fig. 10.

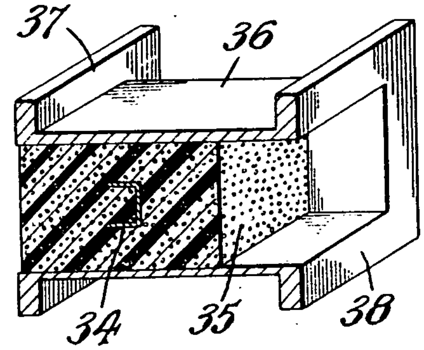

Fig. 11.

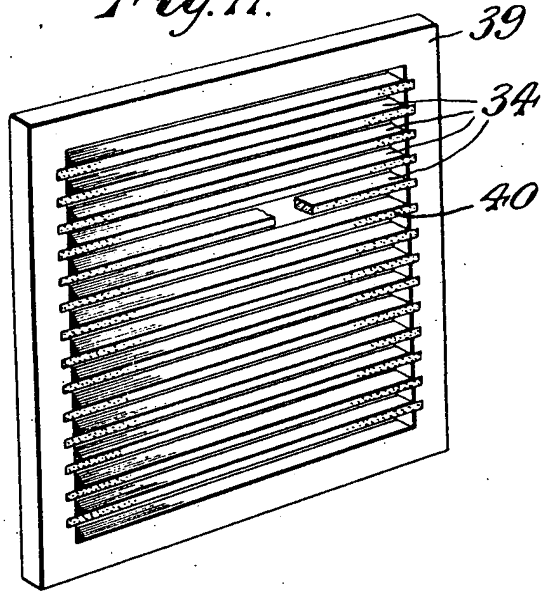

Fig. 12.

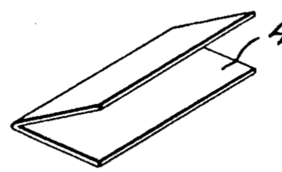

Fig. 13.

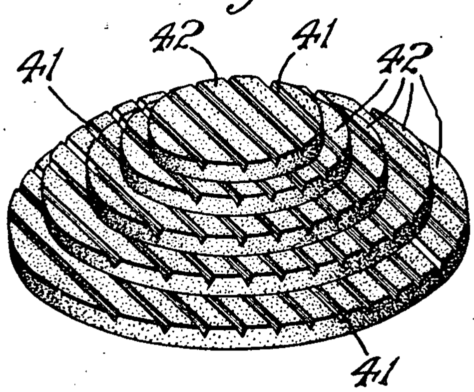

Fig. 14.

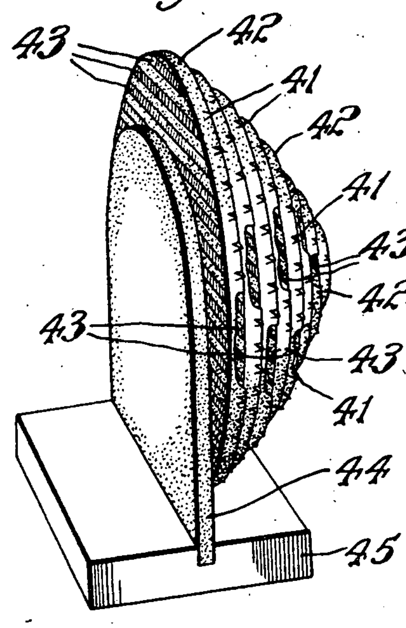

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Fig. 15.

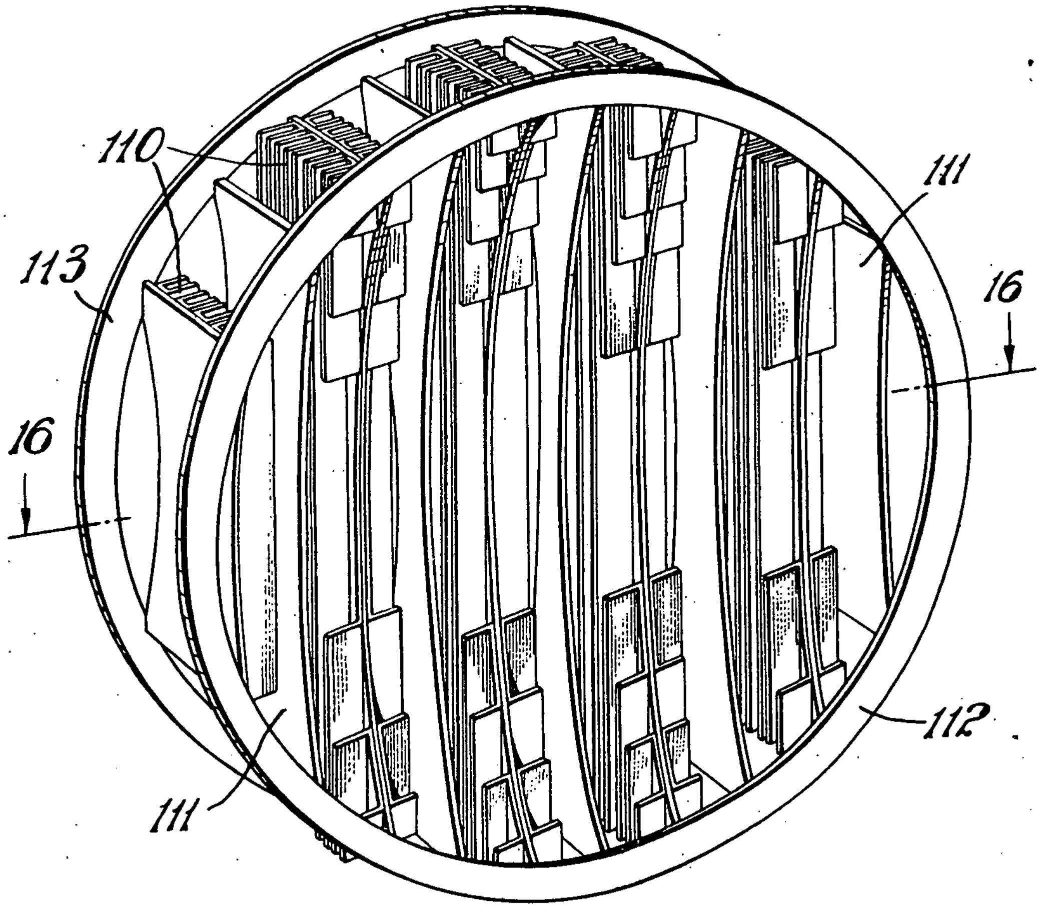

Fig. 16.